EFFECTS OF MULTI-CIRCULAR JET PLATES ON THE SPRAY AND FLAME CHARACTERISTICS OF INTERNAL MIXING AIR-ASSISTED ATOMIZER

SHAHRIN HISHAM BIN AMIRNORDIN

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Universiti Tun Hussein Onn Malaysia

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ABSTRACT

The mixing of fuel and air plays a major role in the spray and flame behaviour, hence, affects the combustion performance and emissions of the internal mixing air-assisted atomizers. This research aims to determine the effects of multi-circular jet (MCJ) plates on the spray behavior and flame characteristics of air assisted atomizers. The MCJ plates provide the primary air entrance into the mixing chamber. The plates are represented by P1, P2, and P3 characterized by the difference in the open area ratio at 17.8, 18.4 and 18.9 respectively. Additionally, P1, P4, and P5 are represented by the jet-hole angles at 0^o, 30^o and 45^o. In the experiments, the spray and flame images of all plates are captured at equivalence ratios of 0.8 to 1.2 using a Digital Single Lens Reflect camera. The flame temperatures are measured using the infra-red imaging technique while the emissions, burning chamber and stack temperature are also recorded using an emission gas analyzer and K-type thermocouples respectively. Then the computational work is conducted by using ANSYS Fluent to visualize the impact of plate geometry on the internal fluid flow and spray structure. Further analysis using both experiments and simulations have been carried out in order to compare between the P5 configuration and swirl. Results show that a decrease in open area ratio and jet-hole angle increases the flame temperature up to 11.4% and 13.8% respectively. The inclined jet-hole also increases the velocity up to 47.7% and turbulence kinetic energy up to 62.4% in the mixing chamber. In comparison between MCJ plate (P5) and swirl, P5 produces 33.8% lower backpressure but produces higher flame temperature at 4.3%. The result indicates that the MCJ plates are more effective in controlling the spray and flame characteristics of the atomizer. The outcome of this work provides a deeper understanding on the relations of geometry and fuel-air mixing to the characteristics of the internal mixing air-assisted atomizer which will lead to the improvement of burner systems in the future.

ABSTRAK

Campuran udara dan bahanapi memainkan peranan yang penting terhadap ciri-ciri semburan dan pembakaran, seterusnya mempengaruhi prestasi pembakaran dan gas keluaran pengabut terbantu udara jenis campuran dalaman. Kajian ini menentukan kemampuan kawalan geometri plet pelbagai jet bulatan (MCJ) terhadap ciri-ciri semburan dan pembakaran sebuah pengabut terbantu udara. P1, P2 dan P3 mewakili nisbah kawasan terbuka iaitu 17.8, 18,4 dan 18.9. P1, P4 dan P5 pula mewakili sudut condong kemasukan udara pada 0°, 30° dan 45°. Di dalam eksperimen, imej semburan dan api kesemua plet diperolehi pada nisbah kesetaraan dari 0.8 hingga 1.2 menggunakan kamera Digital Lensa Tunggal Refleks. Suhu api diukur menggunakan kaedah pengimejan infra merah manakala gas pelepasan, suhu kebuk pembakaran dan suhu pelepasan gas masing-masing menggunakan penganalisa gas pelepasan dan penyukat suhu jenis-K. Simulasi menggunakan perisian ANSYS Fluent digunakan untuk mendapatkan gambaran terperinci kesan perubahan geometri plet terhadap aliran bendalir dan struktur semburan. Seterusnya analisa menggunakan eksperimen dan simulasi dijalankan untuk membandingkan plet P5 dan pemusar. Keputusan menunjukkan pengurangan nisbah kawasan terbuka dan sudut lubang udara masing-masing meningkatkan suhu api kepada 11.4% dan 13.8%. Sudut lubang udara pula dapat meningkatkan halaju sebanyak 47.7% dan tenaga kinetik gelora sebanyak 62.4% di dalam kebuk campuran. Perbandingan antara plet MCJ (P5) dan pemusar menunjukkan P5 menghasilkan tekanan balik yang lebih rendah sebanyak 33.8% tetapi menghasilkan suhu api yang lebih tinggi sebanyak 4.3%. Ini menunjukkan plet MCJ berkesan untuk mengawal ciri-ciri semburan dan api sesebuah pengabut. Hasil dapatan kajian ini membolehkan pemahaman lebih mendalam antara hubungan geometri dan campuran udara bahanapi terhadap ciri-ciri pengabut terbantu udara jenis campuran dalaman yang boleh menyumbang kepada penambahbaikan sistem pembakaran pada masa hadapan.

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LIST OF SYMBOLS AND ABBREVIATIONS

°C	-	Degree celcius
μm	-	Micrometer/Micron
2-D	-	Two-dimensional
3-D	-	Three-dimensional
ALR	-	Air-liquid ratio
ASTM	-	American Society for Testing and Material
CFD	-	Computational Fluid Dynamics
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
D, d	-	Diameter
DM	-	Discrete Multicomponent Model
DPM	-	Discrete Phase Models
DSLR	-	Digital single-lens reflex
Eq.	-	Equation
ER	-	Equivalence ratios
fps	-	Frame per second
GLR	-	Gas-liquid ratio
HC	-	Hydrocarbon
kg/h	-	Kilogram per hour
m	-	Meter
mm	-	Milimeter
m/s	-	Meter per second
MCJ	-	Multi-circular jet
MPa	-	Megapascal
MW	-	Molecular weight

N	-	Number of holes
NO_x	-	Nitrogen oxides
O_2	-	Oxygen
OA	-	Open area
p	-	pressure
PDF	-	Possibility density function
PM	-	Particulate emissions
ppm	-	Parts per million
Q	-	Flow rate
SMD	-	Sauter mean diameter
TAB	-	Taylor breakup model
TKE	-	Turbulence kinetic energy
V	-	Velocity
ρ	-	Density

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CHAPTER 1

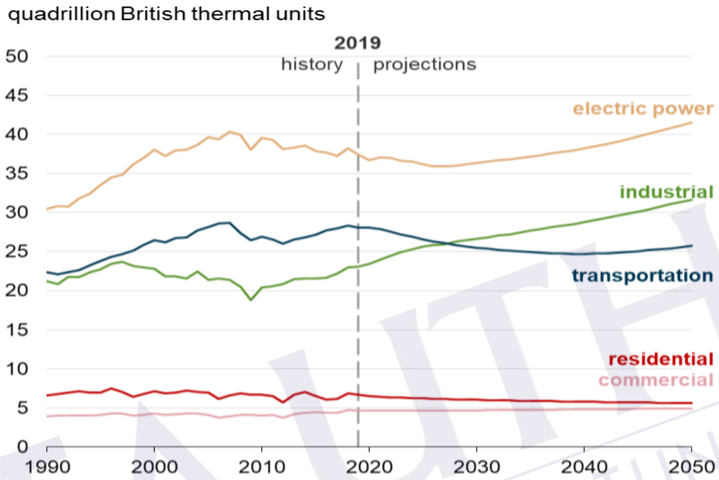
INTRODUCTION

1.1 Background of study

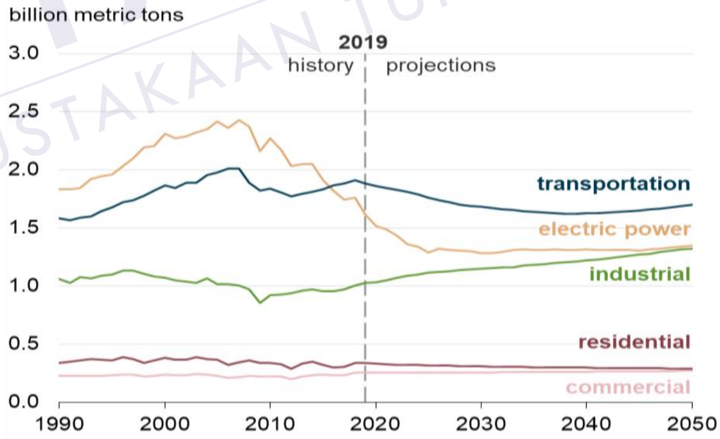
Combustion has been the foundation of the population and industrial growth around the world for the past centuries. There are six major uses for combustion in the industry which are petroleum refining, chemicals, iron and steel, smelting, pulp and paper, and cement. The burning of fuel to produce heat or other forms of power produces combustion, which is part of the industrial processes. However, a trend related to the energy outlook around the world reveals that for the last 10 years, world energy consumption has shown a steady growth at an average of 1.7% growth. In 2019, energy consumption shows that the industrial sector is in the third highest energy requirement and will move to second place by 2025 (Figure 1.1(a)). In addition, petroleum oil ranks the highest in energy consumption from 2019 until 2050. As a result, the growth in energy consumption contributes to the carbon dioxide emission which shows an average of 1.3% growth rate (Figure 1.1(b)) for the past 10 years and continues to increase in the future (Energy Information Administration, 2020).

The global industrial burner industry is in a phase of transition to factory automation and integration of components. However, the needs for improving operational efficiency and reducing the level of emissions remains a trend in developing countries (Persistent Market Research, 2019). Therefore, burners have been used as the integral parts of boilers and industrial heating systems. The key performance targets of a burner system are divided into three. First is the reduction of nitrogen oxides (NOx), carbon monoxide (CO) and particulate emissions (PM).

Second is to maximize system efficiency for reducing carbon dioxide (CO_2) emissions. Last target is to reduce specific fuel consumption. In the burner system, atomizers are the most important component in mixing both the fuel and oxidizer. The atomizer transforms a certain volume of liquid into sprays or other types of dispersion into small drops in order to increase its surface area. It discharges the liquid at high velocity into a relatively slow-moving stream of air or gases (Mashayek & Ashgriz, 2011).



(a)



(b)

Figure 1.1: Energy outlook around the world (a) Energy consumption by sector and (b) Energy-related carbon dioxide emissions by sector (Energy Information Administration, 2020)

Atomizers are categorized according to their working principles and typical applications. Basically, it requires a high relative velocity between the liquid and the surrounding air or gases. The first technique involves a discharge of high-velocity liquid into a relatively slow movement of air or gas, i.e. pressure atomizer and rotary atomizer. The second technique involves the relatively slow-moving liquid exposed to high pressure or velocity of air; known as twin-fluid atomization (Figure 1.2). Typical atomizers are included air-blast, effervescent and air-assisted atomizers (Lefebvre & Ballal, 2010).

Air-assisted atomizers are introduced in order to counter the low-pressure differential of a simplex nozzle, which reduces the atomization quality. Inside the atomizer, pressurized air is used to augment the atomization process at the lowest flow rate. Currently, two configurations of air-assisted atomizers are available with different fuel-air mixing mechanism. In external mixing form, high-velocity gas or steam impinges on the liquid, at or outside the liquid discharge orifice; whereas in internal-mixing configurations, air or gas and liquid mix within the nozzle before discharged through the outlet orifice. The liquid and pressurized air sometimes are supplied through tangential slots to encourage fuel and air mixing, which influence the discharge pattern into a conical form, hence affects the combustion characteristics of the atomizer (Lefebvre & McDonell, 2017; Yatsufusa, Kidoguchi & Nakagawa, 2014). As additional, effects of the outlet shape on the spray angle of effervescent-swirl atomizer also has been determined previously. Results show that swirl atomizer produces widest spray angle for the profiled outlet (Ochowiak *et al.*, 2015). In addition, the swirling motion assisting the fuel and air mixing by producing centrifugal forces will result in a vortex formation within the body (Vigueras-Zuniga *et al.*, 2014; Zhang *et al.*, 2017; Wlodarczak, Ochowiak & Matuszak, 2018; Hreiz, Gentric & Midoux, 2011).

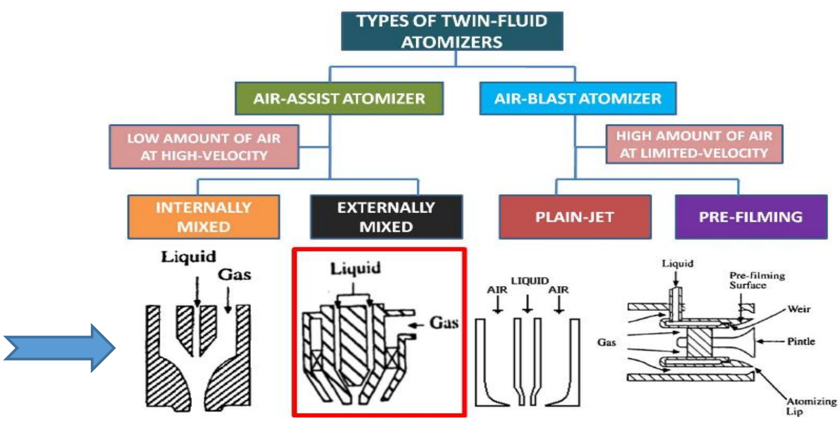


Figure 1.2: Twin-fluid atomizers (Lefebvre & McDonell, 2017)

1.2 Problem statement

Burner combustion in industrial applications is highly complex systems due to various complicating factors of heat transfer during combustion, non-uniform size of spray droplets and complex flow and mixing patterns in the mixing chamber or the combustion chamber. The mixing of fuel and oxidizer takes place in the burner chamber, where the mechanics of mixing process play an important role. The mixing is dependent on the geometry, spatial distribution, momentum of the air flow and influence of any flame stabilization devices such as turbulence generators.

Swirl is a type of turbulence generators used in industrial combustion. It produces a predominant flow mechanism effective in controlling the flame stability and combustion intensity. It utilizes swirling motion to generate a recirculation zone for mixing the fuel and oxidizer and generate compact flame with much higher combustion intensity. It characterizes the size and strength of recirculation to determine effects on flame stability and combustion intensity.

The complexity of the recirculation zone produces non-linear characteristics of flame. As a result, it elucidates the responsible basic process for initiating and sustaining combustion instabilities. The development of the passive and active control methodologies for combustion instabilities are substantial in a current research area (Dunn-Rankin, 2008). In order to control the flame characteristics, it requires the controllability of fuel and air mixing by using the geometry of high blockage plates.

Multi-circular jet (MCJ) plates have been identified as a turbulence generation system that yields large turbulent Reynolds numbers in a compact configuration. It allows highly turbulent and reasonably homogeneous flows inside the nozzle. Although numerous studies have been focused on turbulence generators and its effects on the spray and combustion, there is limited literature discussing alternative solutions on the geometry of primary air entrance particularly by using the MCJ plates in the mixing chamber. It is anticipated that this approach has high potential for improving the fuel and air mixing in the atomizers, hence can assist in controlling the spray combustion from the burner (Coppola & Gomez, 2009).

1.3 Research questions

In order to address the stated issues, the following questions needs to be resolved.

(i) How significant is the effect of MCJ plate geometry on the spray and flame characteristics from internally mixed air assisted atomizer?

(ii) How does the MCJ plate geometry influences the fuel and air mixing and how does it contributes to the spray formation?

(iii) What the different between MCJ plate and swirl in terms of spray and flame characteristics?

1.4 Aims

This research aims to determine the effects of MCJ plates geometrical configurations of primary air entrance on the mixing induced by the two-phase flow of liquid fuel and air inside the mixing chamber of the internal mixing air-assisted atomizer.

1.5 Objectives

The specific objectives of this research are:

(i) To determine the effects of MCJ plates on the geometrical configurations of spray and flame characteristics for the internally mixed air-assisted atomizer.

(ii) To analyse the internal fluid flow inside the mixing chamber and its relation to the spray structure produced by the two-phase flow of fuel and air.

(iii) To compare the spray and flame characteristics, together with the fluid flow mechanism and spray structure of one of the MCJ plates with swirl.

1.6 Research scope

The scope of the study as follows:

(i) Internal mixing air-assisted atomizer is used in this study.

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